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Comparative Life Cycle Assessment of remanufactured liquefied natural gas and diesel engines in China

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ABSTRACT

Life cycle assessment (LCA) is a useful analysis tool to estimate the energy consumption and environmental emissions resulting from economic activities. This study provides a comparative LCA of remanufactured liquefied natural gas (LNG) and diesel engines. Furthermore, the paper identifies the processes that contribute most to energy consumption and environmental impacts during the life cycles of the two engines. Six environmental impacts were considered in this study: global warming potential (GWP); acidification potential (AP); eutrophication potential (EP); photochemical ozone creation potential (POCP); ozone depletion potential (ODP); and primary energy demand (PED). The results show that remanufacturing LNG engines reduces energy consumption by 41.91% compared with remanufacturing diesel engines. The greatest benefit related to the environmental impacts is EP, which is reduced by 73.69%, followed by AP, GWP and POCP, which are reduced by 71.49%, 47.14% and 43.90%, respectively. In addition, the cost benefit of the entire life cycle is also significant for LNG engines. In the life cycle of the two types of remanufactured engines, engine usage causes larger environmental impacts, especially with regard to PED and POCP, and component remanufacturing contributes most to ODP. However, it should be noted that in the remanufacturing stage, because more materials and energy are consumed for the LNG engine, the environmental impacts and costs are higher than those for the diesel engine. Nevertheless, the advantages of remanufacturing end-of-life diesel engines into LNG engines are obvious because of the significant benefits during LNG engine use.

1. Introduction

In 2013, vehicle ownership in China reached 137 million; the manufacturing and use of automobiles consumes a large amount of metal, oil and other mineral resources (CIRN, 2014). The petroleum oil consumption of the automotive industry has outstripped 1/2 of the total petroleum consumption in China; furthermore, automobile exhaust is the main source of atmospheric pollution, which, respectively, contributes 38.5%, 11.7%, 87.6% and 6.2% of the total CO, CO_2, NO_x and SO_2 emissions. Therefore, the transportation sector is the largest source of greenhouse gas (GHG) emissions in China, among which heavy duty truck operations are the main contributor (CMEP, 2013). Statistics indicate that the China per capita reserves of iron, copper and aluminum are only 16.7%, 16.7% and 11.1% of the world's average level, respectively; whereas, the annual consumption of iron, copper and aluminum resources correspondingly account for 67%, 47%, and 50% of the world's production (USGS, 2012). According to the annual global carbon emissions report published by GCP (2013), China contributes the most carbon emissions to the global environment. Natural resource depletion and growing environmental concerns are driving research into alternative, cleaner, and more efficient ways of producing and using energy and recourse (Rose, 2013).

Diesel engine remanufacturing has been recognized for better environmental performance than that of newly manufacturing. In contrast to newly manufacturing, engine remanufacturing preserves much of the product value, which “recycles” the value of the raw material, labor, energy and manufacturing operations of the original engine (Liu et al., 2014). In addition, engine remanufacturing makes a greater economic contribution per unit of product than newly manufacturing. Since 2008, China has attempted to set up several auto parts remanufacturing bases

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under the direction of the National Development and Reform Commission (NDRC, 2006).

Previous studies have verified the benefits of products remanufacturing (Goldey et al., 2010; Seliger et al., 2004; Lund and Hauser, 2003), and the environmental and economic benefits of engine remanufacturing have been documented in other studies (Smith and Keoleian, 2003; Sutherland et al., 2008; Zhu and Yang, 2009; Liu et al., 2014).

To minimize the impact of emissions from vehicles, consumers and organizations are seeking viable, low-carbon alternatives to conventional gasoline and diesel vehicles (Rose et al., 2013). Natural gas, which is generally considered to be a clean and efficient fuel (Li et al., 2011; Lin et al., 2010; Xu and Wang, 2010), is a viable alternative to conventional gasoline and diesel powered vehicles and can significantly reduce vehicle emissions (Tamura et al., 2001; Ma et al., 2013). Because of the significant benefits to the economy and the environment, natural gas vehicles are recognized as the most promising markets in China (NDRC, 2006). Compressed natural gas (CNG) vehicles were developed in China for the mature natural gas compress technology, which reduced GHG emissions and fuel costs compared to conventional, oil-fueled vehicles. However, there are many limitations when using a CNG fueled vehicle; they have the disadvantage of a limited energy storage capacity caused by low energy density (Chen et al., 2009; Meng, 2010) and the high investment of CNG filling, which makes liquefied natural gas (LNG) vehicles more favorable.

LNG is a mixed liquid obtained by refrigerating natural gas at −166 °C to −157 °C at atmospheric pressure (Bernatik et al., 2011; Lu et al., 2003). Because of the high density and elimination of the gas compressor, an LNG station is typically more compact, allowing for less noise and less cost than a CNG station. Therefore, LNG vehicles are more suitable for long trips and heavy-duty vehicles. The use of LNG has shown significant reductions in combustion emissions when compared with gasoline-powered engines (Jang and Lee, 2005; Zhang et al., 2011). Currently, more old diesel engines are remanufactured to LNG engines for heavy duty automobiles.

Withers et al. (2014) completed an economic and environmental assessment of liquefied natural gas (LNG) as a supplemental aircraft fuel, and the results show that aircraft operators can save up to 14% on fuel expenses and lower resource consumption by employing LNG retrofits. Yang (2009) compared LNG buses with diesel buses, and they concluded that the use of LNG buses could reduce energy consumption, CO emissions, and CO_2 emissions. Based on an LCA of LNG heavy-duty vehicles in Europe (Arteconi et al., 2010), when LNG is purchased from a regasification terminal, it provides a 10% reduction of CO_2 emissions compared to emissions from diesel vehicles (Aslam et al., 2006; Jayaratne et al., 2009; Kathuria, 2004; Ravindra et al., 2006).

However, the current state of LCA and comparison studies related to the remanufacturing of LNG and diesel engines is largely absent; this study presents a comparative life cycle assessment of a remanufactured LNG engine and a diesel engine based on reliable and real-time operational data provided by the engine remanufacturing company. The realistic estimations of life cycle emissions and energy consumption can be used as a reference for decision-makers to make an informed strategy when selecting LNG or conventional diesel vehicles.

2. Materials and methodology

2.1. Goal and scope definition

The main objective of this study is to calculate the indicators related to the energy consumption and environmental emissions of two types of remanufactured engines: a diesel-powered engine and an LNG-powered engine. Furthermore, the study compares the two results to assess the potential benefits of LNG fuels.

The two types of engines are remanufactured from the same type of original engine, and the functional unit is defined as "300,000 km driven WD615.68 Engine", with six in-line cylinders, a maximum output power of 250 kW and a total displacement of 9.726 L. The engine is used in heavy-duty trucks for freight transportation. The major technical parameters of the original diesel engine are shown in Table 1. After remanufacturing, the technical parameters of the two types of remanufactured engines are the same as the original diesel engine.

Engine remanufacturing begins with product recovery to the workshops; then, the engine is disassembled, cleaned, inspected, refurbished, and finally reassembled into a remanufactured engine. The six components that can be remanufactured include the following: the cylinder block, the cylinder head, the crankshaft, the connection rod, the gear box and the flywheel shell.

Fig. 1 outlines the scope and boundaries of this study. To simplify the LCA modeling, the following assumptions are made:

- The environmental impacts associated with the transportation of additional materials and the remanufactured engine are not considered because of the identical transport distance and conveyance of the two types of remanufactured engines.
- Most components of the two types of remanufactured engines would be recycled for another remanufacturing period; therefore, the environmental impacts involving the end-of-life landfill or incineration disposal are not considered.
- The two types of remanufactured engines experience approximately identical use conditions (wear rates, hours to failure, etc.), and the service life of both engines is 300,000 km.
- The two types of engines are remanufactured from the same end-of-life engine damage state.

2.2. Method and database

Life cycle assessment (LCA) methodology is applied in this study. LCA is a "cradle-to-grave" approach for assessing the cumulative environmental impacts resulting from the entire product life cycle (EPA, 2006). The data related to the energy requirements and the air/water emissions are gathered from the Chinese Life Cycle Database (CLCD). The CLCD is a local life cycle database developed by IKE Environmental Technology and Sichuan University on behalf of the Chinese market average industrial levels (Liu et al., 2010).

2.3. Life cycle inventory analysis

2.3.1. Additional material production

Additional materials are consumed in diesel and LNG engine remanufacturing, including cast iron, aluminum, rubber, diesel and kerosene. The respective quantities of the main additional materials used in diesel and LNG engine remanufacturing are shown in Table 2.

Table 1
Technical parameters of WD615.68 diesel engine.

Parameter	Quantity	Unit
Weight	875	kg
Volume	9726	mL
Rated power	213	kW
Rated speed	2200	r/min
Torsion	1350	Nm
Torque speed	1300~1500	r/min